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WAVE PROPAGATION IN A DC SUPERCONDUCTING CABLE
PART II: PARAMETRIC EFFECTS*

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Abstract - This paper studies wave propagation in several designs of dc superconducting cables. DC conventional cables are also included for the purpose of comparison. For a multiconductor cable system, undesirable transient voltages may develop across parts that are not designed to withstand high voltages. The effects of several parameters were studied to limit these voltages; these are voltage rating, number of conductors, conductor resistances, earth resistivity, terminal grounding resistances of the "grounded" conductors at the origin and dielectric constants. Voltage rating, conductor resistances, and terminal grounding resistances seem to influence the transient performance of a multiconductor cable significantly. The effect of finite earth resistivity is insignificant.

INTRODUCTION

The propagation characteristics of multivelocity voltage waves in a dc superconducting cable of a specific design were discussed in a companion paper [1]. We showed there that a large fraction of the applied voltage may appear across the "grounded" cryogenic enclosure, which may be the weakest link in the system. A possible solution is to connect the two cylinders of the cryogenic enclosure with metal links at regular intervals along the length of the cable. However, this will increase the heat leak and decrease the efficiency of the system. An alternative is to replace the metallic shorts by nonlinear (e.g., zinc oxide) resistors or properly coordinated spark gaps. It is expected that the heat leak will be substantially decreased by this method, although not completely eliminated. However, the nonlinear resistors will be subjected to extreme thermal stresses. A third possible solution is to vary the cable-design and system parameters to minimize the voltage difference across the two cylinders of the cryogenic enclosure.

This paper discusses the wave-propagation characteristics of three- and four-conductor dc superconducting cables, as affected by the system constraints as well as by the cable constraints. Examples of two- and three-conductor dc conventional cables are also included for the purpose of comparison.

CABLE AND SYSTEM PARAMETERS

Table I shows the pertinent parameters of the cables, which were studied.

TABLE I
Pertinent Parameters of Cables

	4-Conductor 100-/300-kV Superconducting Cable	3-Conductor 100-/600-kV Superconducting Cable	3-Conductor 250-kV Conventional Cable	2-Conductor 250-kV Conventional Cable
Outer radius of conductor 1, r_{1o} (mm)	22.7/19.6	40.0	16.7	16.7
DC resistance of conductor 1, R_{c1} ($\mu\Omega$/m)	0.2/0.55	1009.3	33.14	33.14
Inner radius of conductor 2, r_{2i} (mm)	28.3/42.15	100.0	31.6	31.6
Outer radius of conductor 2, r_{2o} (mm)	35.0/48.45	102.0	35.5	35.5
DC resistance of conductor 2, R_{c2} ($\mu\Omega$/m)	0.2/0.55	13.6	2[illegible].53	286.53
Inner radius of conductor 3, r_{3i} (mm)	45.0/54.9	105.4/124.1	44.1	-
Outer radius of conductor 3, r_{3o} (mm)	49.0/58.9	105.4/125.1	49.5	-
DC resistance of conductor 3, R_{c3} ($\mu\Omega$/m)	440.0/363.6	332.2/282.3	114.83	-
Inner radius of conductor 4, r_{4i} (mm)	90.0/161.0	-	-	-
Outer radius of conductor 4, r_{4o} (mm)	94.0/165.0	-	-	-
DC resistance of conductor 4, R_{c4} ($\mu\Omega$/m)	43.0/24.4	-	-	-
Distance of cable center to earth, h (mm)	98.0/177.7	110.4/129.1	55.4	41.5
Dielectric constants : k_1	2.2	1.0	3.0	3.0
k_2	1.0	3.0	3.0	3.0
k_3	1.0	3.0	3.0	-
k_4	3.0	-	-	-

*Work performed under the auspices of the US Department of Energy.

System Parameters

A 100-kV design of this cable has been described previously under specific system constraints, i.e., the grounding resistance of each of the "grounded" conductors at the origin, Rg = 10Ω and the earth resistivity ρ_g = 100 Ω-m [1]. The grounding resistance of a cable sheath, like the footing resistance of a transmission-line tower, and neutral grounding resistance of a generator or transformer, can be decisive in the wave-propagation characteristics of the cable. One end of the cable sheath may even be left open to inhibit the flow of stray current, which could be several hundred amperes in the vicinity of electric transportation systems or electro-chemical industries. We, therefore, varied the grounding resistance Rg from 1 to ∞.

The analysis becomes simple if it is assumed that the earth is perfect, i.e., an earth of infinite electrical conductivity. In practice this ideal condition is never met. The problem becomes more complex if the long cable is laid not only in regions of divergent earth resistivities but also in layers of earth of different resistivities. Moreover, lack of precise knowledge of the earth resistivity precludes exact numerical computations. In spite of these difficulties, it is worthwhile to study the effect of imperfect earth in order to assess the manner in which attenuation and distortion of voltage waves in a cable takes place. We varied the earth resistivity from 0 to 1000Ω-m for all of the cable designs studied.

Four-Conductor Superconducting Cables

A 100-kV design of this cable has been described in the companion paper [1], where the actual resistances of the four conductors were used to compute the wave-propagation characteristics of the cable. In the present study, we have included conductors of zero resistance to determine the effects on attenuation and distortion of the voltage waves.

In the companion paper, the dielectric constant of the annular space in the cryogenic enclosure was assumed to be unity, i.e., k_3 = 1. As the vacuum space inside the cryogenic enclosure is filled with multilayer thermal insulation, its dielectric constant will be higher. A dielectric constant of three (k_3 = 3) was included in the present study to ascertain its effect on the voltage across the space inside the cryogenic enclosure.

The space inside the cryogenic enclosure is designed on the basis of allowable heat leak and is independent of the voltage rating of the cable. Therefore, a higher voltage (300-kV) cable was included to study the effect of cable voltage rating on the voltage across the enclosure space.

Figures 1 to 4 show the step responses of a 100-kV four-conductor dc superconducting cable under various system conditions. Figure 5 shows the step response of a 300-kV four-conductor dc superconducting cable. In each case, the applied voltage wave on conductor 1 is split into four component waves traveling at unequal velocities. All four component waves are present on conductor 1. Three component waves travel on conductor 2; two waves on conductor 3, and one single voltage wave of small magnitude travels on conductor 4 (nearest to earth). That component wave (of small magnitude) which is present on all four conductors at x = 0 is highly attenuated within a short distance from the origin. This wave

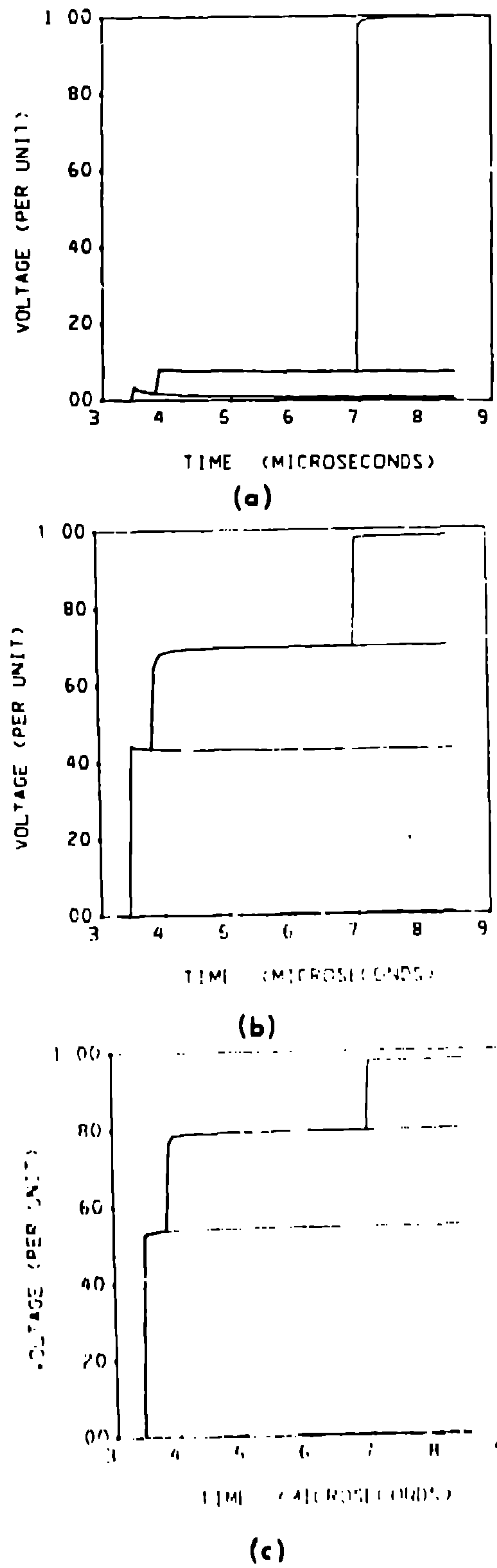


Fig. 1. Step response of a semi-infinite 100-kV four-conductor dc superconducting cable at x = 1 km. Effect of grounding resistance Rg at x = 0. Earth resistivity ρ_g = 100 Ω-m. (a) R_g = 1Ω; (b) R_g = 100 Ω; (c) R_g = ∞. Four, three, two and one component waves travel along conductors 1, 2, 3, and 4, respectively. The component wave which is present on all four conductors is highly attenuated and is not discernable in the figures.

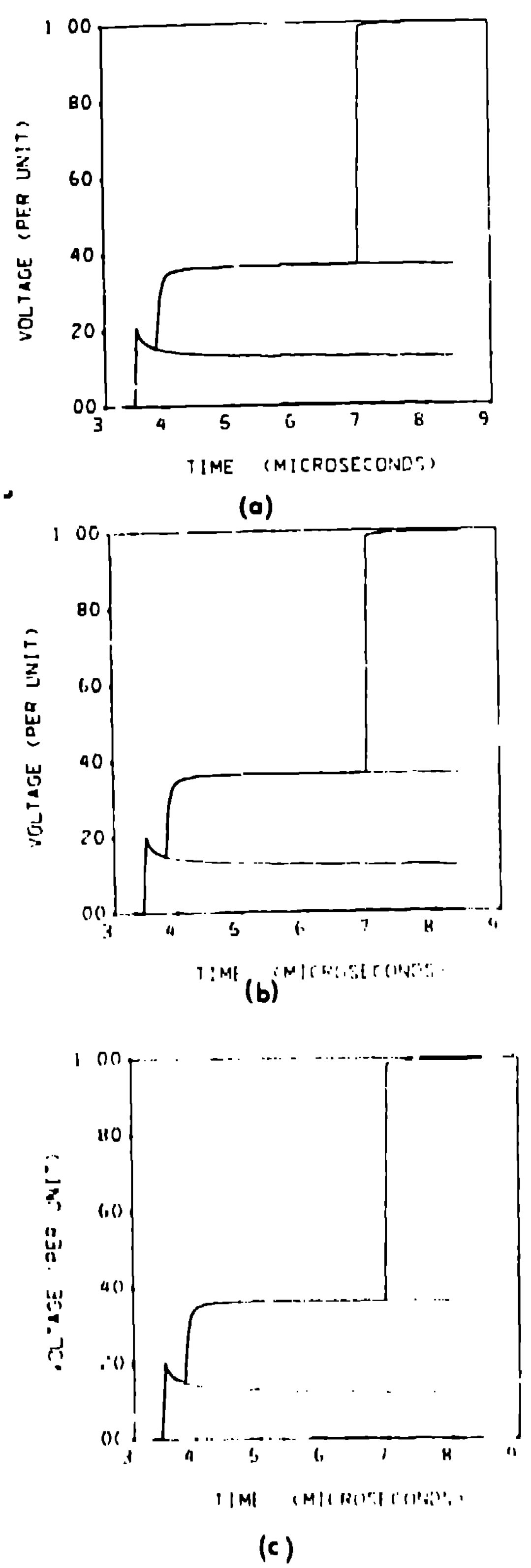


Fig. 2. Step response of a semi-infinite 100-kV four-conductor dc superconducting cable at x = 1 km. Effect of earth resistivity ρ_g. Grounding resistance R_g = 10 Ω at x = 0. (a) ρ_g = 0; (b) ρ_g = 1 Ω-m; (c) ρ_g = 1000 Ω-m.

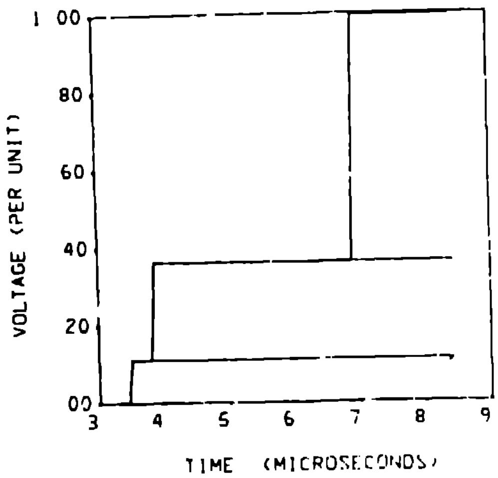


Fig. 3. Step response of a semi-infinite 100-kV four-conductor dc superconducting cable at x = 1 km. Conductor resistances neglected. R_g = 10 Ω at x = 0; ρ_g = 100 Ω-m.

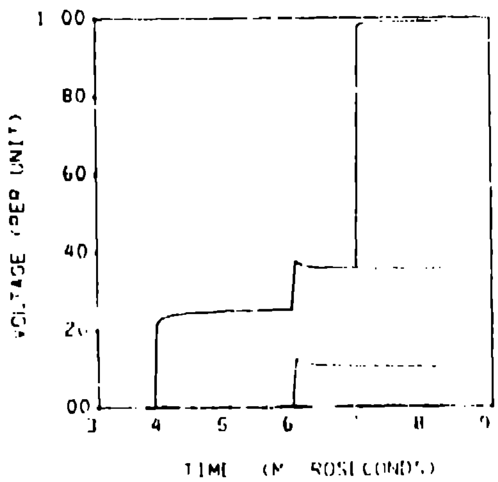


Fig. 4. Step response of a semi-infinite 100-kV four-conductor dc superconducting cable at x = 1 km. Effect of dielectric constant. R_g = 10 Ω at x = 0; ρ_g = 100 Ω-m; k_3 = 3.

is not discernable in any of the figures except Fig. 2a, which represents zero earth resistivity (ρ_g = 0).

Three-Conductor Superconducting Cable

The three-conductor superconducting cable is an alternate design, more suitable for lower power ratings (Fig. 6). The dielectric is at ambient temperature, being thermally isolated from the high-voltage superconductor by the cryogenic enclosure. The inner cylinder (stainless steel) of the cryogenic enclosure is intimately connected to the high-voltage superconductor throughout the length of the cable. Therefore, this combination constitutes conductor 1. The outer cylinder (copper) of the cryogenic enclosure is connected to conductor 1 at the terminals. This is conductor 2. A lead sheath (not shown in the figure) that encloses the dielectric is conductor 3. The electrical load circuit is completed through another similar cable.

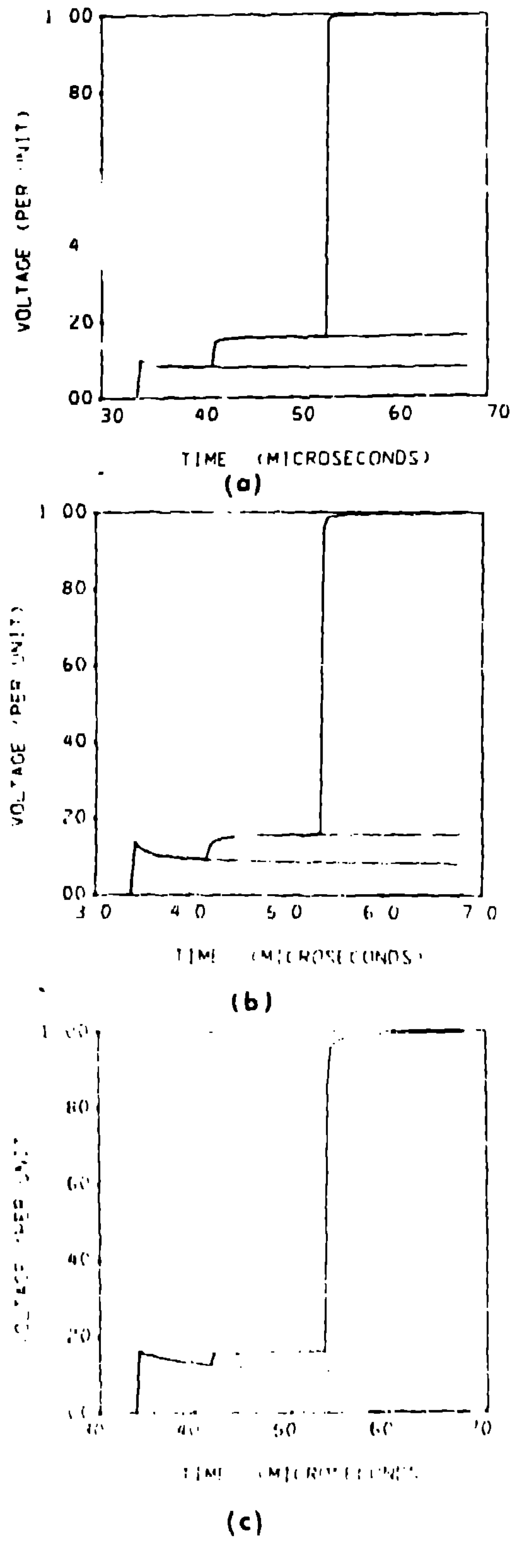


Fig. 5. Step response of a semi-infinite 300-kV four-conductor dc superconducting cable. R_g = 10 Ω at x = 0; ρ_g = 100 Ω-m. (a) x = 100 m; (b) x = 1 km; (c) x = 10 km.

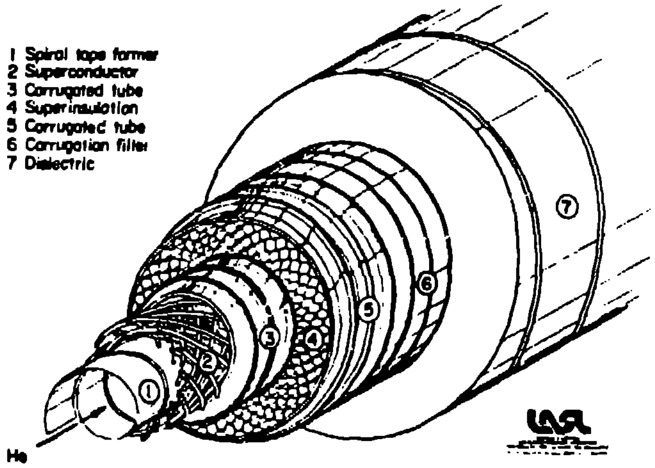


Fig. 6. Conceptual design of a three-conductor dc superconducting cable.

The transient current is assumed to be expelled by the superconductor into the stainless-steel cylinder. Two voltage ratings (100 kV and 600 kV) were considered for this study.

Figures 7 and 8 show the step responses of 100- and 600-kV three-conductor dc superconducting cables under various system conditions. The applied voltage wave on conductor 1 is split into three component waves traveling at unequal velocities. All three component waves are present on conductor 1. Two component waves travel on conductor 2, and one single wave of small magnitude travels on conductor 3. Similar to the four-conductor superconducting cable system, the component wave which is present on all three conductors is of small magnitude at the origin and is highly attenuated within a short distance. This component is not discernable in any of the figures.

Two and Three-Conductor Conventional Cables

The model for the three-conductor conventional cable was derived from the 250-kV dc submarine cable laid between the north and south islands of New Zealand [2]. Conductors 1, 2, and 3 are assumed to be concentric cylinders made up of copper, lead, and galvanized steel, respectively.

The two-conductor model for this study is similar to the three-conductor model but without the galvanized-steel armour.

Figures 9 to 14 show the step responses of 250-kV three- and two-conductor dc conventional cables. The three-conductor cable carries three component voltage waves, and the two-conductor cable carries two component waves. In each system, one component wave is very small in magnitude and is highly attenuated to a negligible value within a short distance from the origin, except for ρ_g = 0.

DISCUSSION

Effect of Grounding Resistance

Figure 1 shows the effect of grounding resistance on the voltage propagation in the 100-kV, four-conductor dc superconducting cable. A lower grounding resistance would stress the major dielectric

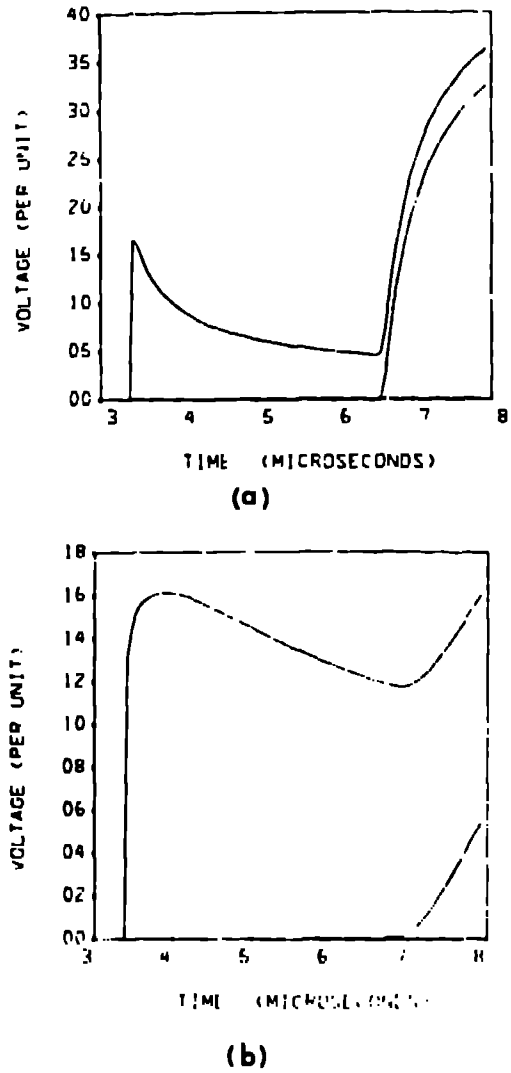


Fig. 7. Step response of a semi-infinite 100-kV three-conductor dc superconducting cable. R_g = 10 Ω at x = 0; ρ_g = 100 Ω-m. (a) x = 100 m; (b) x = 1 km. Three, two, and one component waves travel along conductors 1, 2, and 3, respectively. The component wave which is present on all three conductors is highly attenuated and is not discernable in the figures.

nearer to its design stress and would stress the cryogenic enclosure less. However, it should be borne in mind that conductors 2, 3, and 4 may be kept open or connected to earth through a nonlinear resistance at one end of the cable. The cable will be vulnerable if the surge enters through that end.

Figures 10 and 13 show the effect of grounding resistance on the conventional cables. Higher grounding resistances tend to attenuate and distort the wavefronts. For the three-conductor conventional cable (Fig. 10), the voltage on conductor 3 away from the origin is negligible in all cases where the earth resistivity is finite. The voltage across the dielectric between the lead sheath (conductor 2) and the galvanized-steel armour (conductor 3) is reduced by decreasing the grounding resistance. The attenuation rate of this voltage is also increased when the grounding resistance is less. For the two-conductor

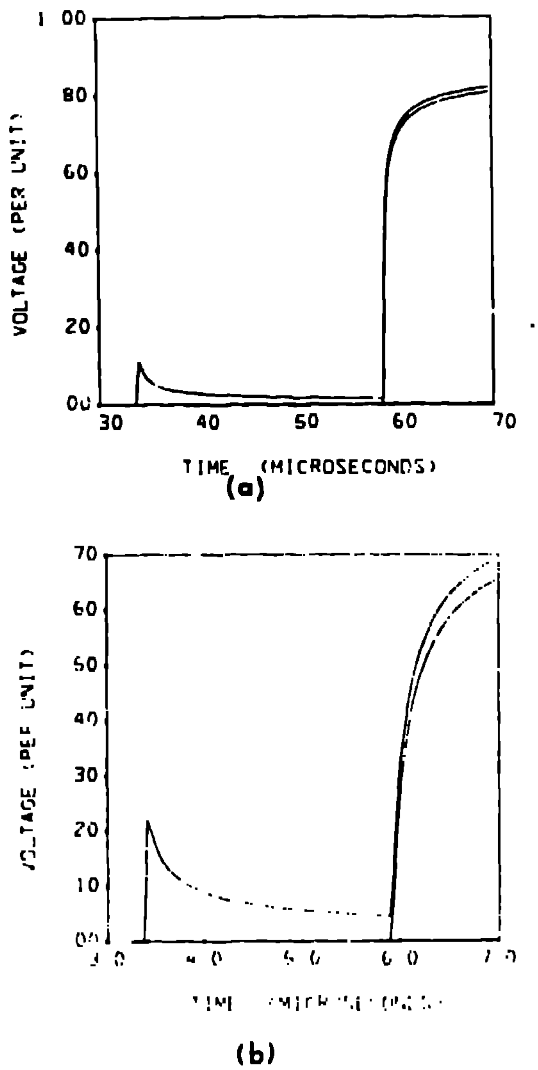
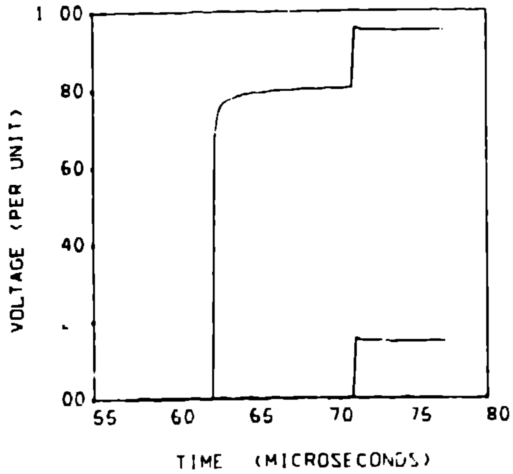


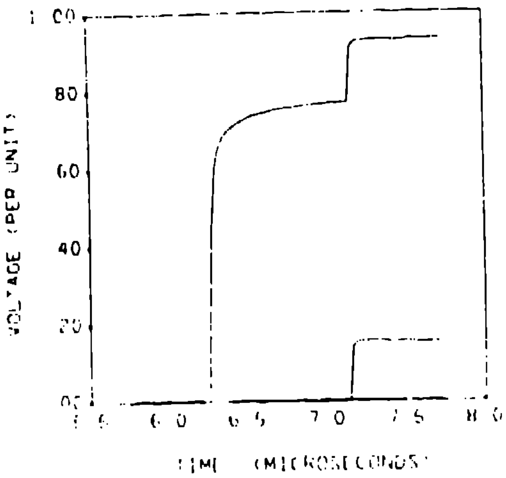
Fig. 8. Step response of a semi-infinite 600-kV three-conductor dc superconducting cable. R_g = 10 Ω at x = 0; ρ_g = 100 Ω-m. (a) x = 100 m; (b) x = 1 km.

nearer to its design stress and would stress the cryogenic enclosure less. However, it should be borne in mind that conductors 2, 3, and 4 may be kept open or connected to earth through a nonlinear resistance at one end of the cable. The cable will be vulnerable if the surge enters through that end.

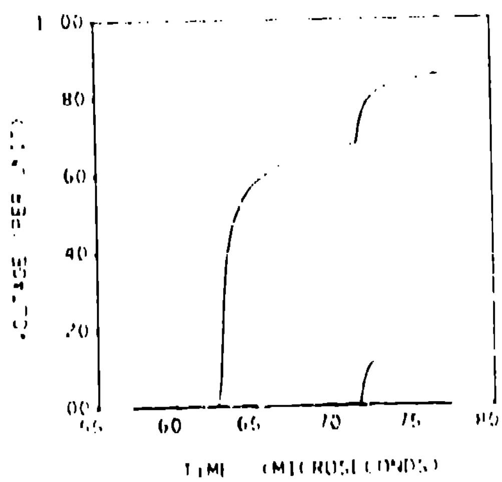
Figures 10 and 13 show the effect of grounding resistance on the conventional cables. Higher grounding resistances tend to attenuate and distort the wavefronts. For the three-conductor conventional cable (Fig. 10), the voltage on conductor 3 away from the origin is negligible in all cases where the earth resistivity is finite. The voltage across the dielectric between the lead sheath (conductor 2) and the galvanized-steel armour (conductor 3) is reduced by decreasing the grounding resistance. The attenuation rate of this voltage is also increased when the grounding resistance is less. For the two-conductor conventional cable (Fig. 13), the voltage on the lead sheath (conductor 2) is negligible for finite earth resistivities. The voltage on conductor 1 is attenuated more with higher grounding resistance.



(a)

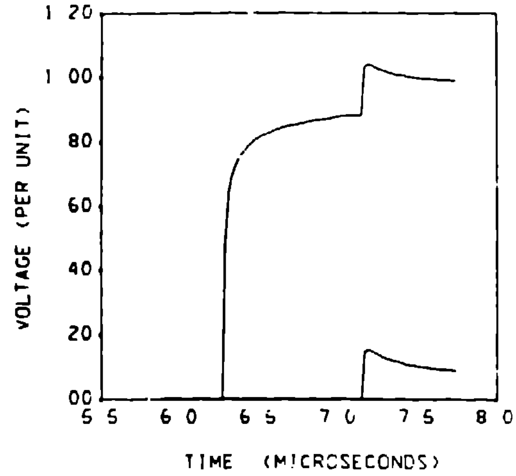


(b)

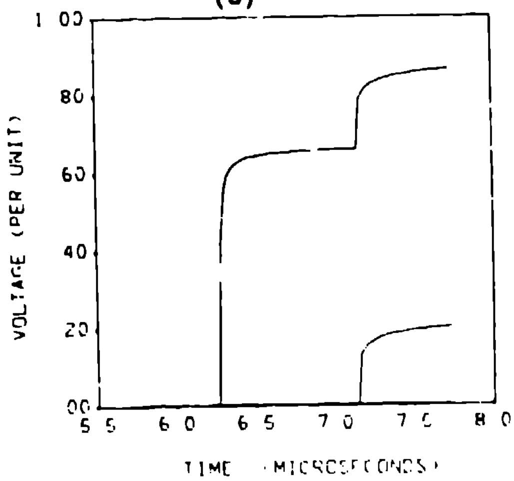


(c)

Fig. 9. Step response of a semi-infinite 250-kV three-conductor dc submarine cable. R_g = 10 Ω at x = 0; ρ_g = 100 Ω-m. (a) x = 100 m; (b) x = 1 km; (c) x = 10 km.



(a)



(b)

Fig. 10. Step response of a semi-infinite 250-kV three-conductor dc submarine cable at x = 1 km. Effect of grounding resistance R_g at x = 0. Earth resistivity ρ_g = 100 Ω-m. (a) R_g = 1 Ω; (b) R_g = 100 Ω.

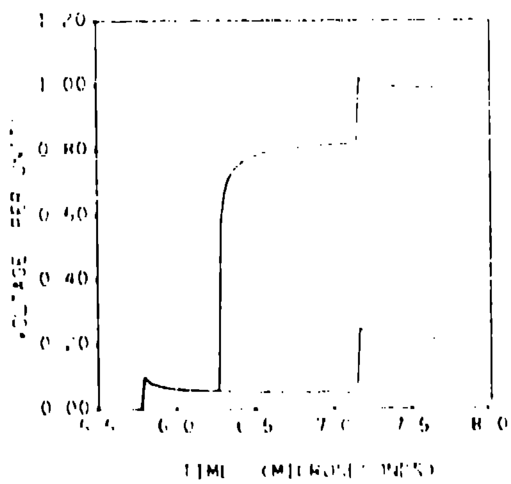
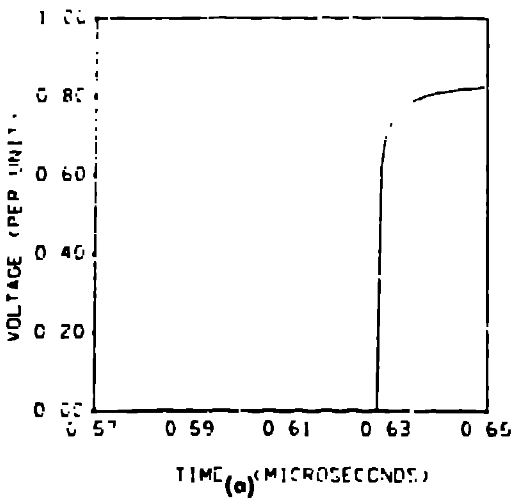
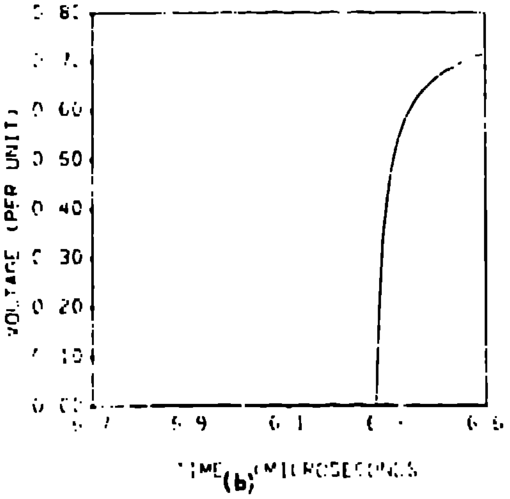


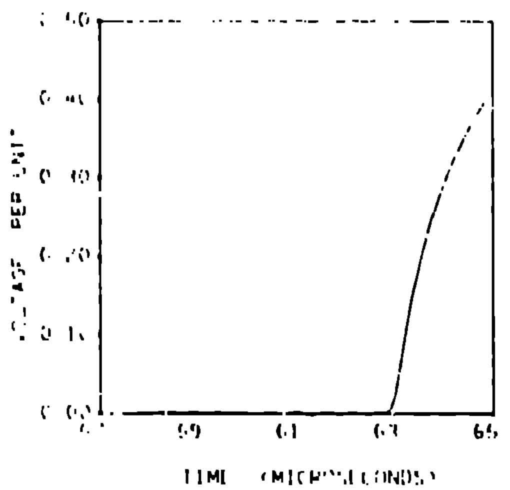
Fig. 11. Step response of a semi-infinite 250-kV three-conductor dc submarine cable at x = 1 km. Earth resistivity, ρ_g = 0 Ω-m. R_g = 10 Ω at x = 0.



(a)

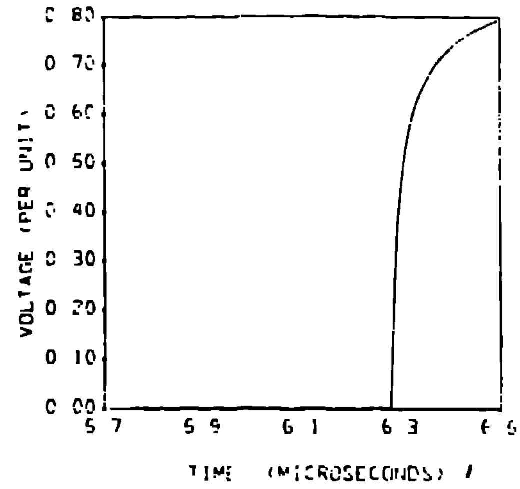


(b)

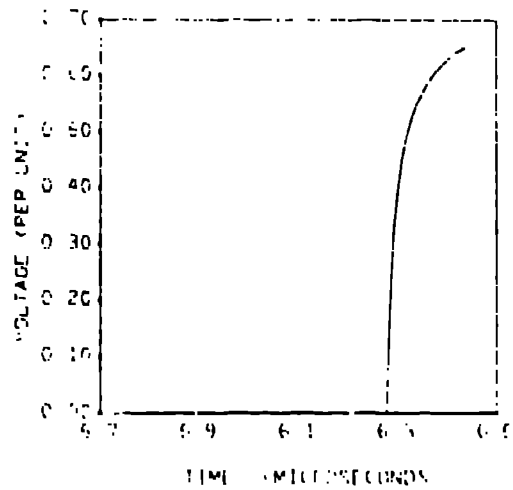


(c)

Fig. 12. Step response of a semi-infinite 250-kV two-conductor dc cable. R_g = 10 Ω at x = 0; ρ_g = 100 Ω-m. (a) x = 100 m; (b) x = 1 km; (c) x = 10 km. Conductors 1 and 2 carry two and one component waves, respectively. The component wave which is present on both conductors is highly attenuated and is not discernable in the figures.



(a)



(b)

Fig. 13. Step response of a semi-infinite 250-kV two-conductor dc cable at x = 1 km. Effect of grounding resistance R_g at x = 0. Earth resistivity ρ_g = 100 Ω-m. (a) R_g = 1 Ω; (b) R_g = 100 Ω.

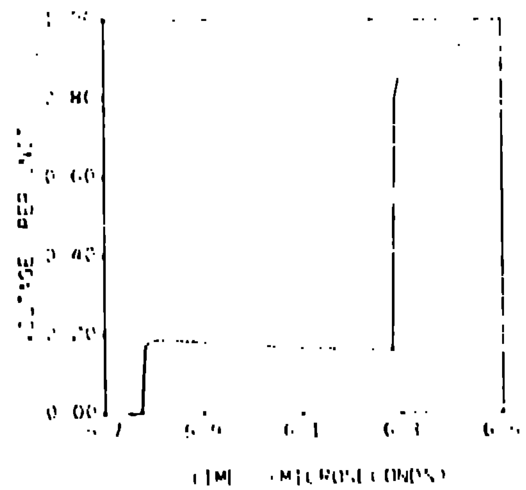


Fig. 14. Step response of a semi-infinite 250-kV two-conductor dc cable at x = 1 km. Earth resistivity, ρ_g = 0 Ω-m. R_g = 10 Ω at x = 0.

Effect of Earth Resistivity

Figure 2 shows the effect of earth resistivity on the voltage propagation in the 100-kV four-conductor dc superconducting cable. Only one component wave is significantly affected by the earth resistivity. This component wave is distinguished by the fact that it is the only wave traveling along conductor 4 (physically situated nearest to earth), and that it is also present on the other three conductors along with other component waves. The existence of this component wave (or ground wave) changes the voltage between each conductor and earth without appreciably changing the conductor-to-conductor voltages. It is discernable only when the earth resistivity is zero (i.e., perfect earth). It is highly attenuated within a short distance from the origin ($x = 0$) when the earth resistivity is finite, being insensitive to the actual magnitude of this finite earth resistivity (Figs. 2b and 2c). This was also found to be true for other types of cables.

The effect of perfect earth on the voltage propagation in three- and two-conductor conventional cables is shown in Figs. 11 and 14. The ground wave is more prominent in these two cases than in the dc superconducting cable (Fig. 2a). Comparing in Table I, it should be noted that the larger the distance of the cable center to earth, the lower is the ground wave.

Effect of Conductor Resistance

The effect of neglecting the conductor resistances is shown in Fig. 3. When compared with Fig. 3b of Ref. 1, it will be evident that the effect of conductor resistances is to increase the stress on the cryogenic enclosure. The conductor resistances also decreases the slope of the wavefront.

Effect of Dielectric Constant

In most cases in this study, the dielectric constant of the annular space in the cryogenic enclosure was assumed to be unity. In practice, this vacuum space will be filled with thermal insulation. Assuming a dielectric constant of 3, computations were made of the voltage distribution in the 100-kV four-conductor dc superconducting cable (Fig. 4). As expected, the velocity of the major component wave on conductor 3 was decreased without changing the interconductor voltage differences substantially.

Effect of Voltage Rating of Cable

The wavefronts on a 300-kV, four-conductor dc superconducting cable are shown in Fig. 5. In this case, the major dielectric is stressed more nearly to its design value, and the helium space between conductors 2 and 3 is stressed less. The cryogenic enclosure is also stressed less on a per unit basis. However, assuming a BIL of 750 kV for this 300-kV cable, the highest voltages across the major dielectric, the helium space, and the cryogenic enclosure will be 647, 56, and 103 kV, respectively. This is in contrast with 162.5, 59.5, and 50 kV for the 100-kV design. The cryogenic enclosure of the 300-kV design is stressed about twice as much as that of the 100-kV design. This is not surprising considering the fact that the cryogenic enclosure is designed mainly on heat-leak specifications.

Three-Conductor dc Superconducting Cable

This cable (Fig. 6) is an alternate design that is more suitable for lower power ratings. The inner cylinder of the cryogenic enclosure is intimately connected to the high-voltage conductor (conductor 1) throughout the length of the cable. The outer cylinder (conductor 2) of the cryogenic enclosure is connected to conductor 1 at both ends of the cable. Therefore, the two cylinders of the cryogenic enclosure are at the system voltage under steady-state conditions. Under transients, a voltage difference develops across the cryogenic enclosure (Figs. 7 and 8). As with the four-conductor case, the voltage across the cryogenic enclosure is smaller for a cable of lower voltage rating.

DC Conventional Cables

Computations for dc conventional cables were performed for the purpose of comparison. As Figs. 9 to 11 show, a considerable amount of voltage may develop between the lead sheath and the steel armour of the three-conductor submarine cable. Smaller grounding resistances at the terminals help in reducing this voltage difference. It is of interest to note in Fig. 10a that the voltage on conductor 1 exceeds 1 p.u. However, the voltage across the major dielectric does not exceed 1 p.u.

Wavefronts for a two-conductor cable of the same voltage rating (250 kV) are shown in Figs. 12 to 14. The voltage waves attenuate and slope off as they travel along the cable (Fig. 12). Higher terminal grounding resistance also attenuates the wavefronts (Fig. 13).

CONCLUSIONS

1. Multiconductor cable systems may develop transient voltages across some cable parts that are not normally designed to withstand high voltages.

2. For conventional cables, these voltages may be limited by shorting these parts together at regular intervals.

3. For cryogenic cables, as shorting will produce extra heat leak, properly designed nonlinear resistances or spark gaps at regular intervals would limit these voltages.

4. In addition, proper choice of terminal grounding resistance and conductor resistance will also limit the undesirable voltage differences for all multiconductor cable systems, conventional or cryogenic.

5. Earth resistivity, as long as it is nonzero, does not seem to have significant influence in the overall transient response of the cables investigated, whereas the influences of voltage rating, conductor resistances, and terminal grounding resistance are significant.

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